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Simulation has long been an accepted training tool, but its acceptance as a flight test enhancement or alternative has been much more difficult to attain. The process of developing a validated, high-fidelity simulation is an important step in this acceptance because it builds confidence in the quantitative data that flight test support demands. This confidence opens up a new world of opportunity for support of a variety of projects and exploration of new frontiers. The F/A-18 simulation at the Manned Flight Simulator (MFS) has been used for many of these projects. Two of the most recent and unique are discussed in this paper.

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HIGH-FIDELITY SIMULATION AS A LOW COST ENHANCEMENT TO FLIGHT TEST

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Abstract

Simulation has long been an accepted training tool, but its acceptance as a flight test enhancement or alternative has been much more difficult to attain. The process of developing a validated, high-fidelity simulation is an important step in this acceptance because it builds confidence in the quantitative data that flight test support demands. This confidence opens up a new world of opportunity for support of a variety of projects and exploration of new frontiers. The F/A-18 simulation at the Manned Flight Simulator (MFS) has been used for many of these projects. Two of the most recent and unique are discussed in this paper.

The MFS facility running the F/A-18 simulation was connected via an encrypted data link to the Real Time Processing System (RTPS) facility, which is the telemetry ground station for flight testing at Patuxent River. The simulation was modified to use this link to provide flight test engineers with critical safety of flight data to prevent departure from controlled flight. This data was computed by the simulation using the telemetered aircraft data.

On another project, the simulation was used off line to determine if a correlation between non commanded roll rates at various air speeds and the presence of a specific misrigged surface could be found. The results have been used by the Navy to return many "bent" aircraft with significant reductions in mission capability to nominal flight status.

Introduction

In the current fiscal environment, the search for low cost alternatives for flight time needed to test a new platform or system is a driving concern. The use of high-fidelity simulation can significantly reduce the number of flights required to complete a program. Simulation can also be used to perform and evaluate flight test maneuvers that are much too dangerous to be tested in the real aircraft. But, before a simulation can be used to enhance flight testing, it must gain the confidence of the pilots and flight test engineers by proving that it has the required fidelity.

An engineering simulation that is used to support flight test is an entirely different entity than a training simulation. This must be taken into account when assessing the required fidelity of each modeled subsystem. A trainer must feel like the real aircraft qualitatively, and all of the pilot interfaces must work exactly as on the aircraft. On the other hand, an engineering simulation must be quantitatively accurate with all of the primary displays and interfaces functional, but secondary displays and functions are of lesser importance. Therefore, available funding is spent on engineering simulations to accurately model functions such as aerodynamics, propulsion and flight controls, while functions such as environment, communications, engine start, etc. can be ignored.

The F/A-18 simulation at the MFS is successfully used on a regular basis to support flight test programs at Patuxent River. A better understanding of the usefulness of high-fidelity simulation in

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flight testing can be gained through an examination of the process used to develop the required fidelity, the challenge of achieving user acceptance, and a discussion of specific examples of successfully supported programs by the MFS.

The MFS Facility

The F/A-18 simulation is a part of the MFS facility[1]. It can be used in any of five lab stations: a 40 ft dome, a 6 degree of freedom motion base, a helmet mounted display station, or two engineering development stations as shown in Figure 1.

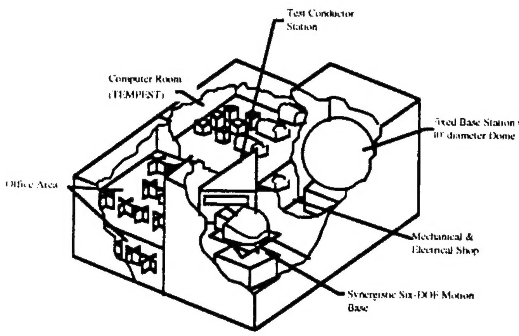

Figure 1 - MFS Facility

The station used is determined by the project: cruise work is normally done in the dome, while take-off and landing work is normally done in the motion base. The helmet mounted display station is being used on a more regular basis for many sessions for a variety of tasks. The cockpit requires only a 30 minute swapout time due to the modular design of the facility and the standard interface on the back panel of the cockpit.

The MFS facility is part of the Air Combat Environment Test and Evaluation Facility (ACETEF). This grouping of interconnected labs is a resource greater than any of the labs on their own. The facility is a fully integrated test facility developed to support multispectral test and evaluation of aircraft and aircraft systems in a secure and controlled environment.

The F/A-18 Simulation

The simulation can be run off-line in desktop mode or in a realtime pilot in-the-loop configuration in one of the lab stations. The F/A-18 simulation being run in a representative configuration is shown in Figure 2.

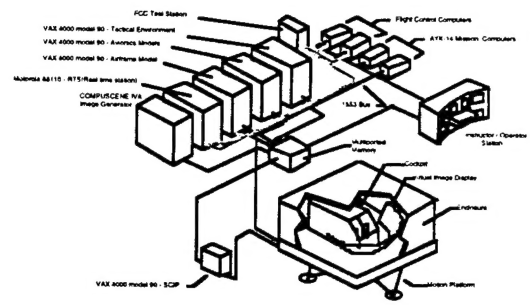

Figure 2 - Representative F/A-18 Lab Station Setup

The simulation is linked with the lab resources using the Simulation Control Executive (SCE) software developed in-house at MFS. Depending on the project, the SCE will configure the simulation to include a variety of options. These options include running with Flight Control Computers (FCC's) and Mission Computers (MC's) in-the-loop via the 1553 bus, and connecting to any of the local ACETEF labs. While these and many other options are available, the strength of the simulation lies in the accuracy of the airframe models.

The F/A-18 simulation has been upgraded to a point where it provides very high fidelity and results that have a high degree of confidence. The upgrades have been concentrated in the areas of aerodynamics, flight controls, actuators, weight & balance, and propulsion.

The most extensive upgrades have been to the aerodynamic math model[2]. The new aerodynamic data tables incorporate the results of parameter identification (PID) analysis as well as the aerodynamic increments associated with rotation about the velocity vector (rotary balance wind tunnel data). The result is an aerodynamic

data base continuous in angle-of-attack from -90° to 90°, sideslip from -30° to 30°, and Mach number from 0 to 2, with representative modeling of the low-speed envelope for both the single-seat and two-seat aircraft.

To validate the simulation a dedicated flight test program of 30 flights was used to gather validation data, and data which could be used for future upgrades[3]. This validation data is very important as it quantifies the accuracy of the simulation. In addition, piloted qualitative evaluations are important to get an idea of the fidelity of the simulation, the transport delays, and to get pilots comfortable with its use as another test tool. The cost of these thirty flights is quickly recovered by reducing the number of flights required for future flight tests because of the use of the simulation.

Currently, the simulation is used heavily for flight test support, accident investigations, flight controls and avionics work. Two recent projects include support for an asymmetric stores envelope expansion flight test program, and support of a program to identify misrigged surfaces on the F/A-18.

Asymmetric Store Loading Envelope Expansion

In a unique application of simulation, the MFS F/A-18 simulation was used to provide real-time feedback of critical aerodynamic and flight control data to flight test engineers during a test flight for the purpose of risk reduction. To accomplish this, a recently developed link between the simulator and telemetry station was used. The MFS was linked to the Real Time Processing System (RTPS) via a T1 line with encryption/decryption capabilities[3]. This link shows great potential to improve flight testing by using the simulation in a variety of ways - only one of which will be examined here.

MFS - RTPS Link

A high level pictorial representation of the configuration used for the asymmetric stores envelope expansion program is shown in Figure 3.

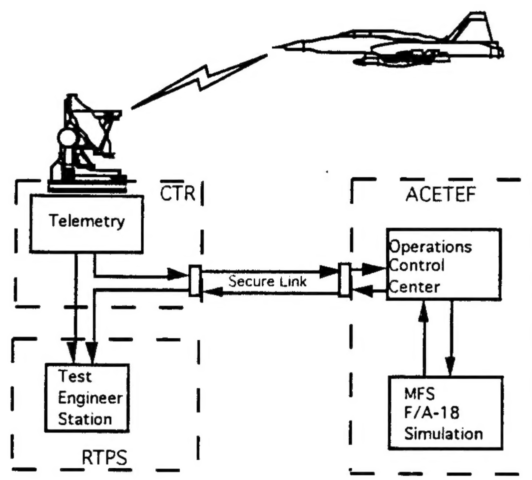

Figure 3 - MFS - RTPS Link

Nominal safety of flight and test data are telemetered, saved and displayed at the RTPS ground station. In addition, certain data is transported via the secure link to the MFS. For this application, the F/A-18 simulation was modified to allow the incoming variables to overwrite the simulation variables and control the simulation. Aircraft states, atmospheric conditions, pilot inputs, etc. come from the actual aircraft and the simulation tracks the real aircraft. In return, the simulation sends information back to RTPS that would be otherwise unavailable. This information includes data that can not be accessed or determined on the aircraft, and data that is specially calculated using the simulation.

Simulation Generated Data

For this program, the challenge was to find a way to graphically represent the amount of roll control power the aircraft had at any point in time. Specifically - when is the pilot in danger of not having enough roll authority to counter the asymmetry. Two methods were developed to address this problem: (1)

determine the ratio of current rolling surface deflection against the maximum possible at the current flight condition, and (2) determine the ratio of the current rolling moment due to the asymmetry against the moment that would be generated by an opposing full roll input. The numerators are determined directly from aircraft data, while the denominators are simulation derived quantities.

This task is more complex then it may appear at first. There are a total of 8 surfaces that work in concert to produce rolling moments. The digital flight controls determine the mix of these surface deflections and deflection limits. The limit on each individual surface is a complex series of functions which are dependent on the flight conditions.

Surface Deflection Method

This method was developed to give an indication of the roll control surface travel that is still available for a given flight condition. Because of the number of surfaces involved and the non-linearity of the aerodynamics, this method is not useful for determining actual roll power available. It is, however, useful in knowing what percentage of the rolling surfaces deflection remains. The simulation returns the percentage of rolling surface used as follows:

$$\text{Roll\_surface}_{used} = \frac{\Sigma\text{rolling\_surface\_deflections}_{actual}}{\Sigma\text{rolling\_surface\_deflections}_{max}}$$

where Σroll_surface_deflections$_{actual}$ is the summation of differential stabilator, aileron, leading edge flap (LEF), and trailing edge flap (TEF) from the aircraft. Σroll_surface_deflections$_{max}$ is the summation of the maximum allowable deflections of these same surfaces at the given flight condition. These maximum deflections are calculated using the simulation. To calculate these values the roll axis control law subroutines were executed using all telemetered data except that either a full left stick or full right stick input was used depending on the attempted direction of roll. The dynamic filters were removed from the control

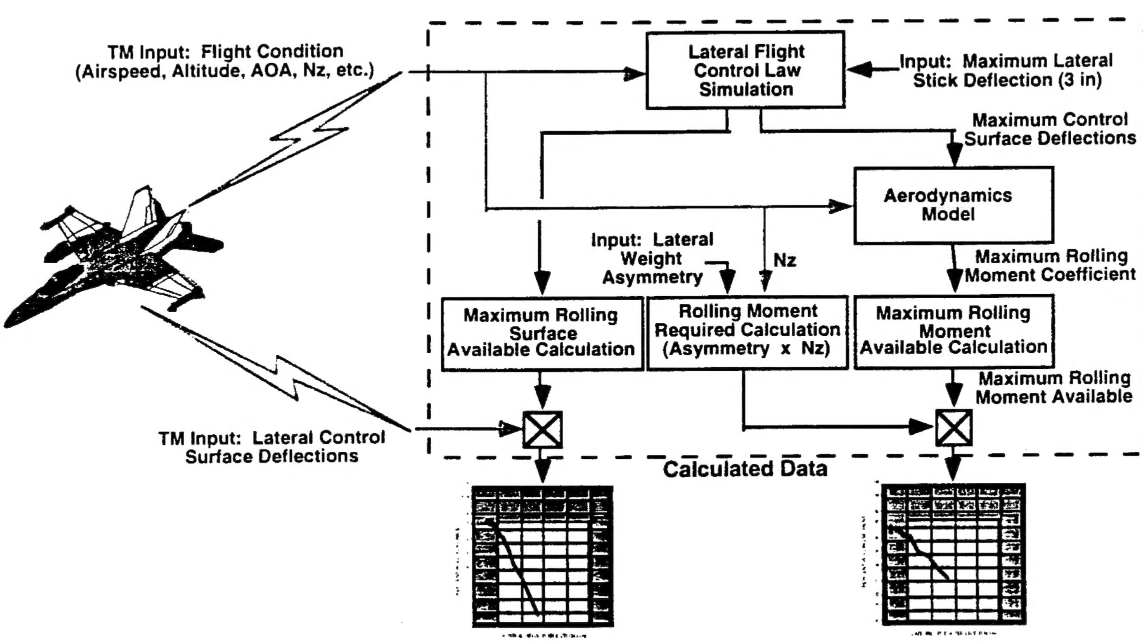

Figure 4 - Simulation Calculated Parameters

laws so that the control surface deflection limits could be determined immediately. A simple block diagram of the simulation modifications is shown in Figure 4.

Rudder inputs were unnecessary because the F/A-18 has a full authority rolling surface to rudder interconnect (RSRI).

The delay between the calculation of the data and the display to the test engineer was 0.1 seconds due to the synchronization of the simulator and telemetered data.

Rolling Moment Method

The ratio of rolling surface deflection, while useful, does not give a true picture of the roll power. To get a clearer picture, the rolling moment method takes the surface deflection method one step further. All of the surface deflections that were calculated for the full stick input were sent to a modified version of the aerodynamics routine. This routine calculates the roll moment coefficient and thereafter the rolling moment generated by the full stick input. This is the maximum rolling moment the pilot can generate at that particular flight condition.

Rather than comparing this moment to the current total rolling moment, it is compared to the current rolling moment due to the asymmetry. A better representation of loss of roll control is presented in this manner. The current moment generated by the asymmetry is calculated at RTPS and sent to the simulation as part of the data stream. This asymmetry is then multiplied by the filtered normal acceleration signal from the aircraft FCC accelerometer. The result is the rolling moment due to the asymmetry, which may be compared to the maximum rolling moment using the equation:

$$\text{Roll\_Moment}_{\text{used}} = \frac{\text{Roll\_Moment}_{\text{asymm}} \times \text{Normal\_Load}}{\text{Roll\_Moment}_{\text{max}}}$$

This value is also sent to RTPS for display to the flight test engineer. It is the most important value sent.

RTPS Use of the Simulation Data

After being sent to RTPS the data is used as part of a display used for real-time departure prevention. Presented in Figure 5 are the parts of the display that use the simulation data. This display is the first of it's kind at NAWCAD to merge simulation and aircraft data to be used real-time for flight test risk reduction.

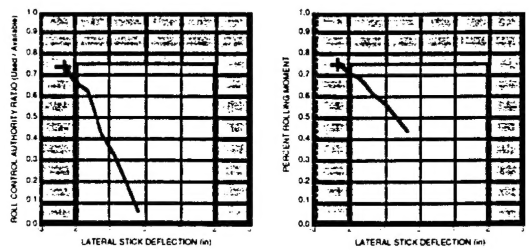

Figure 5 - Simulation Generated Displays

Both simulation calculated variables are presented in similar fashion as shown above. They are plotted against lateral stick so that a quick comparison of pilot command and effect is apparent. The outer limits of each box represent full left and right stick on the horizontal axis, and either roll moment ratio or surface deflection ratio from 0 to 1 on the vertical axis. The light inner box represents the safety factor that was applied for safety of flight calls. These factors were determined to be 75% for the ratios, and 2 inches (or 2/3) for lateral stick. The display used the current point plus the past few points to show the trend in a glance.

This use of simulation to enhance flight test data was very successful. The displays presented important information in a manner that was quickly digestible, and actually allowed engineers to get comfortable interpreting trends. This information made the display useful not just for safety of flight, but also for a

conceptual understanding of what was going on throughout the maneuvers.

Correcting Aircraft Control Surface Rigging

Many F/A-18 fleet aircraft currently in use suffer from uncommanded rolling moments. These moments are generated by control surfaces that have either become misshapen or have warped due to age or have been improperly rigged. On some aircraft these moments are so large as to create a departure hazard. These moments can normally be eliminated if it can be determined which surface (or surfaces) is creating the moment. Unfortunately, the highly augmented nature of the flight control laws makes it very difficult to isolate the surface that is creating the moment. In the past, some of the aircraft were improved by the contractor using a trial and error method approved for rerigging. The requirement now was to develop a formal yet simple procedure to identify the misrigged surface and the action required such that it could be routinely performed in the fleet by persons with no specialized training.

The F/A-18 simulation was used to help address this problem. By working backward from simulated known misrigged surfaces, a search was made for a pattern that would help identify the offending surface. On each control surface of the aircraft, various misrigs were added and the simulation trimmed at various airspeeds. The simulation was then run to get the local roll rate maximum. This analysis was done in the cruise, full flaps, and half flaps configurations. Only the cruise analysis will be presented here as the other configurations were analyzed in the same manner. The test matrix for the cruise configuration is shown in Figure 6. For this program, a matrix as sparse as 80 points was all that was necessary to identify the trends in cruise configuration. The matrices for PA and PA1/2 were the same except speeds of 150, 175, 200, and 250 knots were used. In practice the cruise configuration is used on the actual aircraft.

Surfaces misrigged	Aircraft speeds	Amounts of misrig
Ailerons	200 kts	0.5 deg
Stabilators	300 kts	1.0 deg
Rudders	400 kts	1.5 deg
LEF's	500 kts	2.0 deg
TEF's		

Figure 6 - Cruise Misrig Variables

To allow implementation of the test matrix, the production simulation was modified so that a misrig could be added to any control surface by adding a constant bias to the control surface position at the actuator model output. This biased position was then used for all downstream calculations, including aerodynamics. This implementation gave the most physically representative system.

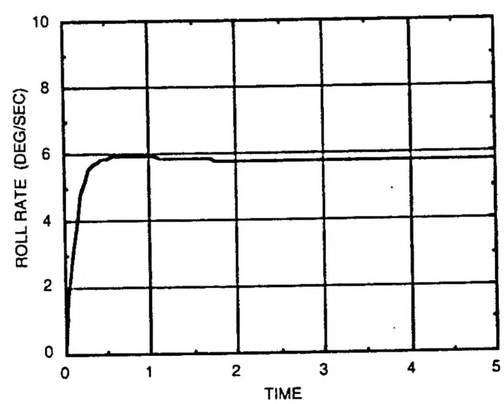

Figure 7 - Stabilator Misrig Run

A representative run is shown in Figure 7. The simulation was trimmed at 400 knots and 20,000 feet. The stabilator was then misrigged 2 degrees and the simulation was run. Notice that a steady roll rate was achieved within half a second. This roll rate was recorded and the process repeated for all points.

The series of graphs in Figure 8 shows the results of the simulation analysis of misrigs for the cruise configuration. Note that the characteristic curve for each surface is shown. The actual graphs are a series of curves that are similarly shaped but differ in magnitude with the magnitude of the misrig.

This data shows that there is a unique relationship between uncommanded roll rate and airspeed for a misrig of each surface. Therefore, these graphs can be the basis for designing a flight test profile to identify flight control surfaces on the actual aircraft that are causing the uncommanded roll rates.

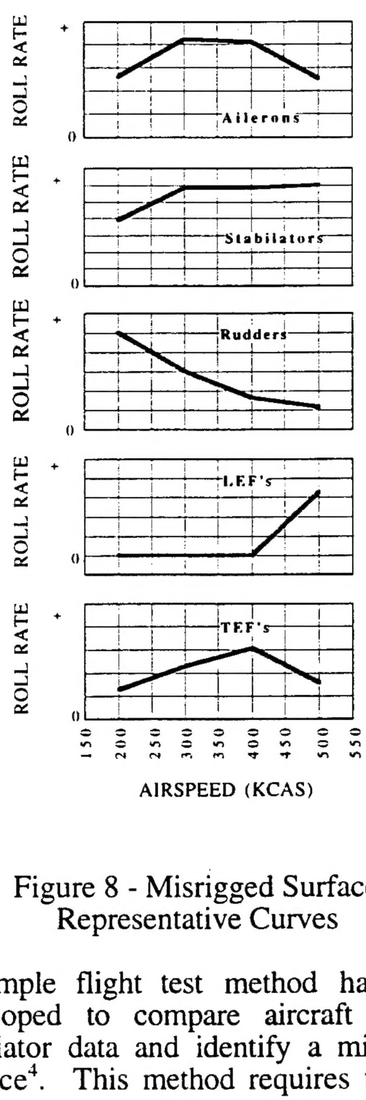

Figure 8 - Misrigged Surface Representative Curves

A simple flight test method has been developed to compare aircraft to the simulator data and identify a misrigged surface[4]. This method requires that the pilot take off and transition to cruise configuration without using lateral trim, stabilize at 200 knots, release the stick, and measure the time it takes to roll 30 degrees. He then repeats this for each point that was run in the simulator (Figure 6). Once back on the ground, the time to roll can be converted to an average roll rate and plotted vs. airspeed as with the simulator data. A simple match between the aircraft trace and one of the surface traces is usually obvious. The fact that the simulator used maximum roll rates and the flight test uses average roll rates is not an issue as the curves are the same shape with minor magnitude differences.

The problem is slightly more complicated if more than one surface is misrigged. Usually one of the surfaces is the dominant contributor, and one of the trends from the simulator can be identified. This surface is dealt with first, then the flight test is repeated. Once the first surface is corrected, the second surface becomes clear. In the simulator, pilots have been able to identify up to three simultaneous misrigs. In practice there has not been the need to identify more than two simultaneous surfaces.

This technique has been highly effective in correcting control surfaces on many F/A-18 fleet aircraft that were exhibiting uncommanded roll rates[4]. The extension of this technique to other highly augmented aircraft, is a simple, cost effective way to improve the flying qualities of our current assets.

Conclusions

These examples of the use of simulation to support flight test are only two of many that the MFS uses on a daily basis to support its customers. Simulation is a valuable tool, and as such is limited only by the imagination and creativity of the engineers that use it. There is no program that cannot be supported in some way by utilizing simulation.

In the past, simulation was used almost exclusively in a stand alone manner. While this is still useful today, using simulation in concert with other tools can multiply the effectiveness of the effort.

The following are lessons that have been learned:

• Refine the simulation to get the highest possible fidelity given the financial reality.

• Verify the simulation both qualitatively and quantitatively and have the results readily available for the customer.

• Convince users of the fidelity of the simulation, AND make sure they know the limitations and constraints which they must obey to obtain valid results.

• Simulation is one of many tools - find other available tools that compliment the simulation and use them in concert.

• Work closely with customers and seek their input - they often have ideas that aren't constrained by our simulation paradigms.

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